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Radiation detectors based on synthetic diamond

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Summary. — The state of the art of Chemical Vapor Deposition (CVD) diamond detector technology is reviewed and its applications in several fields, such as high-energy physics, radiotherapy and nuclear fusion reactors, are described. The impact of the newest front-end electronics design is discussed. Finally, recent innovative developments using laser techniques are also illustrated together with very recent results.

PACS `81.05.ug` – Diamond.
PACS `29.40.Wk` – Semiconductor detectors for nuclear physics.
PACS `29.40.Gx` – Tracking and position-sensitive detectors.

1. – Introduction

Polycrystalline diamond is produced by Chemical Vapour Deposition (CVD) from energized H_2(98%)+CH_4(2%) gas mixtures. Diamond is a semiconductor with outstanding material properties such as high radiation hardness, high free carrier mobilities, very low leakage current, and very high thermal conductivity.

High-quality CVD diamond can be used as radiation detector which is in many ways much simpler than silicon radiation detectors. In fact, diamond is not doped; metallic electrodes are simply placed on device surface; the signal is collected by a charge sensitive amplifier; no leakage current compensation is needed; no cooling is required.

Diamond detectors are successfully employed in several scientific and technical fields where the signal is not a concern but radiation tolerance and fast response are mandatory. These applications are mainly heavy ions detection (see GSI experiments at Darmstadt in Germany) and beam or X-ray monitoring (intense synchrotron light, FEL, and inertial

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fusion sources) [1]. Nevertheless, in the last years large size and free-standing polycrystalline diamond are produced with high quality and good reproducibility, making this material attractive for very demanding applications such as tracking detectors and bi-dimensional dosimeters for Intensity Modulated Radiation Therapy (IMRT). Anyway, the commercial availability and the cost of high-quality diamond wafers are of some concerns and despite the enormous effort currently taking place in the field, there is still not a clear picture on the future.

Diamond quality is strongly related to the charge collection distance $\lambda = \lambda_e + \lambda_h$, which is the distance e-h pair drift apart, due to the electric field E, before trapping or recombination occurs. For MIP particle counting mode, the induced electric pulse is given by $q_{ind} = 36 \frac{e^-}{\mu\mathrm{m}} \lambda[1 - \frac{\lambda}{d}(1 - e^{-\frac{d}{\lambda}})]$, where d is the distance between biasing electrodes. For X-ray ionization chamber mode, the induced current is given by $J_{ion} = eF_0\eta\frac{\lambda}{d}$, where e is the electron charge, F_0 is the radiation incident flux, and η is the quantum efficiency. It is empirically observed that larger values of λ lead to less polarization and better dynamic response.

2. – Applications

Diamond detectors are sensitive to any kind of radiations: from deep UV light to X- and γ-rays, from α and β radiations to neutrons, so that a large variety of applications can be envisaged [2].

Single-channel devices, readout by a quite traditional electronic chain, are used when position information is not required, such as in monitoring and dosimetry. Electrodes patterning in micro-strips and pixels by lithography are necessary in tracking and vertexing reconstruction, such as in high-energy physics. In addition, advanced interconnection techniques between sensors and front-end electronics are required to realize multi-channel hybrid devices.

2·1. *Detectors for tracking in high-energy physics*. – Diamond hybrid pixel prototypes were assembled with standard ATLAS pixel electronics (FE- I3) using Ti-W metallization and IZM solder bump-bonding [3]. An entire ATLAS module, made of high-quality poly crystal diamond and equipped with 16 front-end chips, showed more than 97% of working channels and a global threshold setting as low as 1500 e^-. In addition, a single-crystal diamond sensor was bump-bonded to a single chip showing almost ideal performance. All these prototypes, after calibration in the laboratory with radioactive source, were fully characterized in high-energy particle beams before and after irradiation, showing very good results in terms of efficiency and in-time spatial resolution.

2·2. *Pixelated detectors for IMRT and deep UV*. – Modern radiotherapy is based on IMRT, which delivers dose to a 3D target irradiating the patient through many photons beams in different directions, and entry points, in order to maximize the radiation field on the tumor and minimize it on healthy tissues. The LINAC accelerator is equipped with multi-leaf collimators and the radiation detection system is typically based on commercial single side silicon strip detectors.

The tissue equivalence, linearity over three dose decades, and radiation hardness make diamond a very attractive material for next generation of IMRT radiation detection system. For this applications the signal-to-noise ratio is not of a concern but linearity and stability of the response are crucial (about 0.5% precision). Very promising is poly crystal diamond in null-bias operation [4], where a Schottky barrier at the metal-diamond interfaces is created and an active region is established, due to the built-in electric field. In this condition the charge carriers do not cross the diamond bulk and the dynamic response is unaffected by trapping mechanism due to bulk defects.

In IMRT the spatial resolution, pixellated information, and large area are required features, making CVD diamond a good candidate. Similar requirements are needed in the development of fast, stable, and visible-blind deep UV photodetectors for many applications such as: satellite-borne observations, chemical and medical analyses, high-resolution photolithography, and vacuum UV spectroscopy. Diamond films are quasi-transparent to high-energy X-ray photons, but penetration depth of deep UV and very soft X-ray is small and the e-h pair generation takes place near the material surface.

2˙3. *Detectors for monitoring and nuclear spectroscopy.* – Polycrystalline diamond for Beam Condition Monitoring (BCM) or Beam Loss Monitoring (BLM) were pioneered by the BaBar, Belle, and CDF Collaborations. All four experiments at LHC installed diamond beam monitoring, demonstrating that diamond is a mature material for this application [3].

Being diamond a low-Z material it can be used for beta and alpha monitoring in presence of high gamma background. Thermal neutrons can be detected using converters, like ^{10}B or ^{6}Li, and fast neutrons using reactions on carbons ^{12}C. In both cases short-range energetic ions are generated and large signals detected [5]. Spectroscopy-grade detector can be manufactured using single crystal diamond grown by omoepitaxy from a seed of special oriented HPHT (High Pressure High Temperature). This method limits the single-crystal diamond size to the HPHT substrate size of $\sim 5 \times 5\,\mathrm{mm}^2$.

3. – Low noise and fast front-end for pixels

The negligible leakage current and the small detector capacitance result in a low intrinsic noise of the diamond detectors which might compensate the disadvantage of the small signal size if sufficiently low noise front-end electronics, operating at effective threshold below 1000 e$^-$, were available. Vertically integrated pixels may be the solution to many limitations of the traditional CMOS technology. In fact, multilayer device structure can keep analog and digital pixel-level electronics on different tiers, reducing substrate and power distribution cross-talks, increasing complexity and functionality, and reducing pixel size [6].

Presently, the electronic noise is the limiting factor of the excellent time resolution of CVD diamond detectors. Time resolution is given by the signal rise-time and signal-to-noise ratio according to the formula: $\sigma_T = T_{rise}/\frac{S}{N}$. Assuming $T_{rise} = 1\,\mathrm{ns}$ and $\frac{S}{N} = 20$ the formula predicts a 50 ps time resolution for the ideal case. For a MIP signal this can be achieved only if the first stage amplifier is integrated on the detector and an adequate amplification-shaping stage follows [7]. For pixel detectors the power consumption is a strong limitation but pixel readout chip with excellent time resolution (better than 100 ps) are developed for the Gigatracker of NA62 experiment [8].

4. – Laser techniques applied to diamond detectors

Laser techniques applied to diamond detectors were pioneered by G. Parrini and collaborators. They mechanically bonded a diamond sensor on a silicon die by lightening, across the transparent diamond, the diamond-silicon interface, using a 355 nm wavelength laser having 20 ps pulse width [9]. This is a first step for realizing a pixel detector for MIP

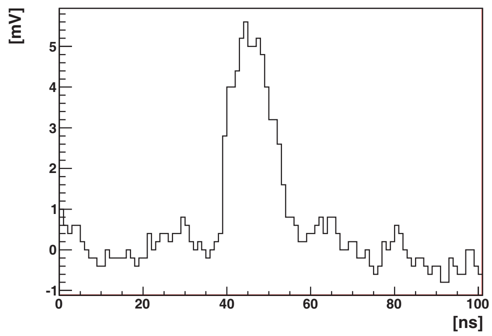

Fig. 1. – Typical time profile of the signal induced by a 120 GeV pion in a diamond with laser-graphitized electrodes.

or a MicroElectrode Array (MEA) for applications in biology [10]. In these devices both silicon and diamond require post-processing: silicon chip needs of Through Silicon Vias (TSV) and diamond sensor of surface and buried ohmic electrodes. The group fabricated conductive graphitic structures on diamond surface and bulk using the 2nd harmonic of a Nd:YAG Q-switched laser source with $\lambda = 1064\,\text{nm}$ and an energy $< 100\,\mu\text{J}$ for 8 ns pulse width, proving that the structures seem suitable for detectors [10].

Following this promising approach we realized, in the L^3 laboratory at the Università del Salento, nano-graphitic electric contacts on a detector-grade diamond material, using a 193 nm UV ArF excimer laser, which is absorbed by diamond. The laser emitted 20 ns long pulses with an energy of about 160 mJ/pulse at 10 Hz repetition rate and a transverse size of about $20 \times 10\,\text{mm}^2$.

Preliminary measurements showed that the pad detector with graphitized contacts is capable to detect ionizing radiation in counting mode (see figs. 1 and 2, where measurements are made with a front-end electronics having a rise time of 2 ns and a gain of 8 mV/fC). Work is in progress in order to fully characterize the contact in terms of speed, noise, stability, radiation damage and aging.

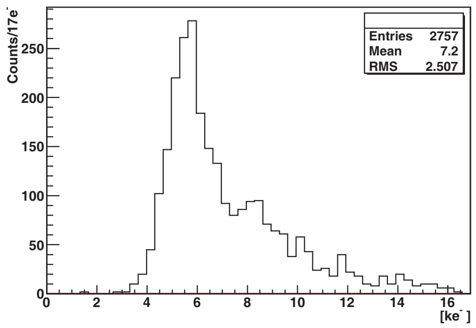

Fig. 2. – Charge distribution observed for 120 GeV pions in a diamond with laser-graphitized electrodes.

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REFERENCES

[1] Berdermann E. for the NoRDHDia, *Nucl. Phys. News*, **19** (2009) 25.
[2] Zhao S., *Characterization of the Electrical Properties of Polycrystalline Diamond Films*, Ph.D. Dissertation, Ohio State University (1994).
[3] Asner D. *et al.*, *Nucl. Instrum. Methods A*, (2010) DOI: 10.1016/j.nima.2010.04.096.
[4] Bruzzi M. *et al.*, *Diam. Relat. Mater.*, **20** (2011) 84.
[5] Almaviva S. *et al.*, *J. Appl. Phys.*, **103** (2008) 054501.
[6] Re V., *Presented at IWASI 2011* (2011) DOI: 10.1109/IWASI.2011.6004681.
[7] Pietraszko J. *et al.*, *Nucl. Instrum. Methods A*, **618** (2010) 121.
[8] Garbolino S. *et al.*, *10th International Conference RD11., Florence, 6-8 July, 2011*, `http://pos.sissa.it/archive/conferences/143/033/RD11_033.pdf`.
[9] Lagomarsino S. *et al.*, *Appl. Phys. Lett.*, **96** (2010) 031901.
[10] Parrini G. *et al.*, *10th International Conference RD11., Florence, 6-8 July, 2011*, `http://pos.sissa.it/archive/conferences/143/017/RD11_017.pdf`.